Data Processing for Winters 1997 and 1998 Central Labrador Sea

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ABSTRACT

This work describes several techniques to process data collected in the central Labrador Sea during the winters of 1997 and 1998 as part of the Labrador Sea Deep Convection Experiment. Ship-based observations (CTD and intake logs) and float data (profiling isobaric floats and fully Lagrangian floats) are intercalibrated and used to estimate trends in mixed layer properties during the winter of 1998. RAFOS records are used to calculate the horizontal position of fully Lagrangian floats utilizing two methods.

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1 Instrumentation

Deep Lagrangian Floats (DLFs) are designed to follow water motions in three dimensions and thus be close to fully Lagrangian [see *D'Asaro et al.*, 1996; *Steffen and D'Asaro*, 2002; *D'Asaro*, 2003]. The 1998 deployment (January 26–March 24) of these floats from the R/V *Knorr* in the central Labrador Sea yielded five high quality horizontal tracking records. The DLFs measured temperature to millidegree accuracy and pressure to about one decibar. One float, given here as an example, sank after deployment and recorded a temperature profile (Fig.2). After its week-long autoballast cycle, the float lightened itself and rose. Mixed layer depths were shallow in early 1998, and the float was caught below the mixed layer. It was eventually entrained into the convecting layer where it recorded nearly continuous vertical motions. At the end of the mission, the float performed a (non-Lagrangian) profile.

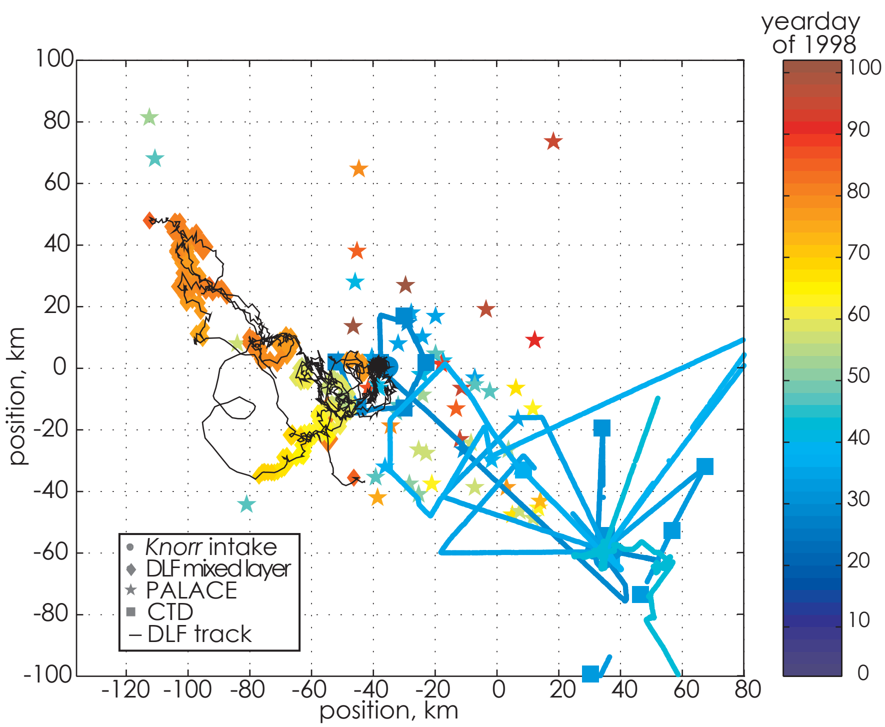

Figure 1. Data used here include PALACE float data shown as stars, CTD data as squares, R/V *Knorr* intake data as dots, DLF data collected within the mixed layer as diamonds, and DLF tracks shown as solid black lines.

Intensive CTD surveys were conducted by the R/V *Knorr* from January 25 to February 12, 1998. Concurrent with the surveys, intake temperature and salinity val-

ues were recorded by shipboard instruments. These provide a near synoptic estimate of sea surface variability.

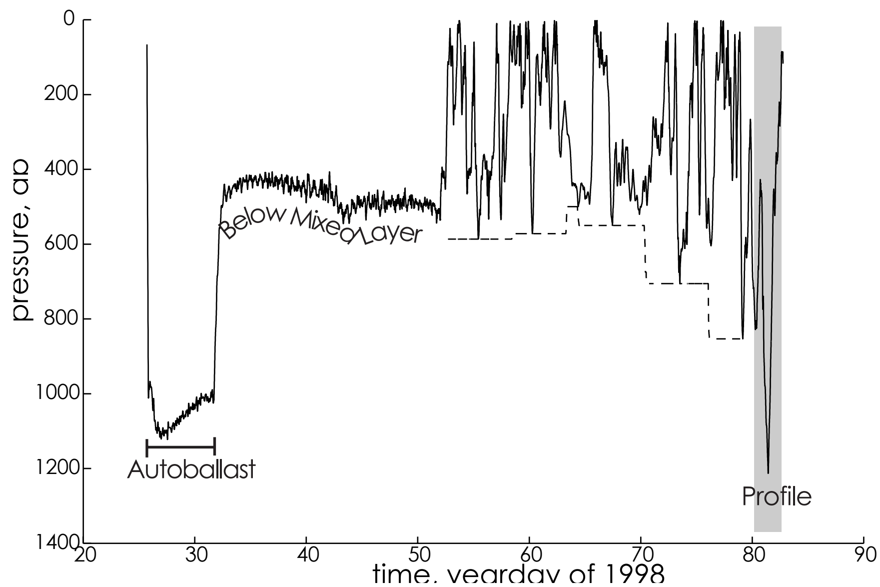

Figure 2. Pressure record with time for DLF 33 (solid) with mixed layer depth estimate (dashed). Shaded grey region indicates non-Lagrangian, end of mission profile. The mixed layer depth estimate was made by excluding data collected outside the mixed layer (utilizing temperature as an indicator) then selecting the maximum pressure recorded within a five day window.

Over 200 PALACE (Profiling Autonomous Lagrangian Circulation Explorers) floats were deployed during the winters of 1997 and 1998 [*Lavender and Davis*, 2002]. These isobaric floats drift for several days at a prescribed depth (in this case, 400 m or 700 m) then surface, communicate via satellite, and return to depth, thereby constructing profiles of temperature and salinity on a pre-programmed cycle of 3.5 days to 20 days. They were deployed intensively in the same area as the DLFs. PALACE float data collected during the first 100 days of 1998 in an approximately 200-km box surrounding the region of the 1998 DLF deployments were provided by Kara Lavender. This PALACE float data is comprised of 74 profiles of temperature and 69 profiles of salinity from 14 floats. PALACE float measurements have an expected accuracy of 5 db in pressure, 0.005°C in temperature, and 0.01 psu in salinity [*Davis et al.*, 2001]; corrections for instabilities in PALACE salinity measurements are discussed in section 2.

2 Data Intercalibration

R/V *Knorr* temperature and salinity intake data were, at times, collected simultaneously with CTD profiles. Comparison with the corresponding CTD records in the region northwest of the former ocean weather station Bravo revealed the intake to register 0.03°C warm and 0.22 psu salty. Corrections of these magnitudes were subtracted from the intake data. CTD profiles taken at the time of DLF deployments and the floats' initial profiles were in good agreement (to 0.01°C).

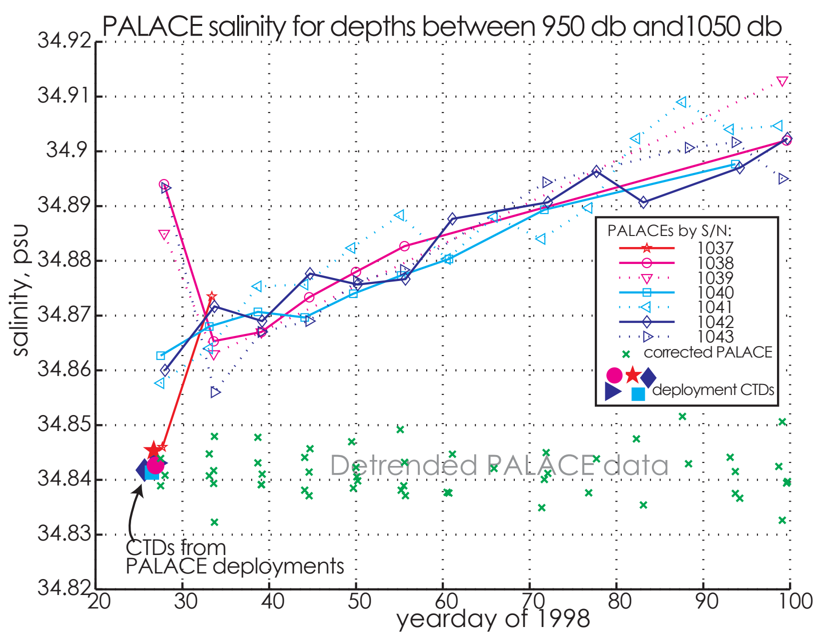

Figure 3. Salinity values averaged 950–1050 db for PALACE floats and CTD profiles taken at the time of the PALACE deployments. Individual floats are shown as lines, solid symbols are from CTD data, detrended PALACE data are shown as "x" symbols.

PALACE float salinity data is subject to sensor drift and instabilities [*Davis et al.*, 2001]. To account for this behavior, all PALACE floats for which more than one profile was available were analyzed (53 profiles from 7 floats). To reduce the influence of mixed layer deepening and vertical mixing, the deepest data possible was selected. Depth was limited by deployment CTD depths—slightly below 1000 db. Averages of PALACE salinity for the depth range 950–1050 db were plotted against time by float. Salinity data drifted ∼0.06 psu in 80 days (Fig. 3). The initial profiles for several floats (serial numbers 1038, 1039, and 1043) were erratic, and these first data points

were excluded from consideration. Data from float 1037, with only two profiles, was also excluded. A linear trend, constructed utilizing all the remaining data, and an offset to align PALACE data with deployment CTDs was removed (corrected data shown as “x” symbols in Fig. 3). A similar analysis of the PALACE float temperature data revealed no trend and good agreement with deployment CTDs, to within the 0.02°C statistical scatter.

3 Mixed Layer Properties

Data included in this analysis were collected over a period of months. To compare data collected while the mixed layer was convecting and thus changing properties, it is necessary to determine and subtract background values (spatial averages) of the variables. Meteorological data, early CTD profiles, and simple one-dimensional mixing schemes can be used to provide estimates of mixed layer depth, temperature, and salinity. However, analysis not shown here found that such estimates failed to adequately reproduce the restratification observed during 1998, probably because the one-dimensional schemes cannot adaquately model restratification. Instead, combining the data provided by the PALACE floats and DLFs, the R/V *Knorr* intake logs, and the CTD profiles allows the determination of a background level of mixed layer depth, salinity, temperature, and density based on observations that are temporally and horizontally distributed. This section describes how these “background” values of mixed layer properties can be determined.

Each PALACE and CTD profile was summarized by one value for mixed layer temperature, salinity, and density. Because there is very little variability in temperature and salinity within a convecting mixed layer for one profile, determination of mixed layer depth allows a representative value for each variable to be obtained. Mixed layer depths were first estimated objectively, as the deepest location where $\Delta\theta/\Delta P$ was 1/20 the peak value (where $\Delta\theta$ was the difference in potential temperature and ΔP was the difference in pressure between vertically adjacent profile data points). This procedure was followed by manual confirmation. Six PALACE profiles were rejected as recording no obvious mixed layer base; these were not used further in this analysis. Nine PALACE profiles, several having two peaks in $\Delta\theta/\Delta P$, were manually adjusted to the visually apparent mixed layer base. Examples of these three profile types are shown in Fig. 4. From this determination of mixed layer depth, averages of potential temperature, salinity, and density were made for depths 50 db below the surface to 30 db above this mixed layer depth to provide mixed layer averages.

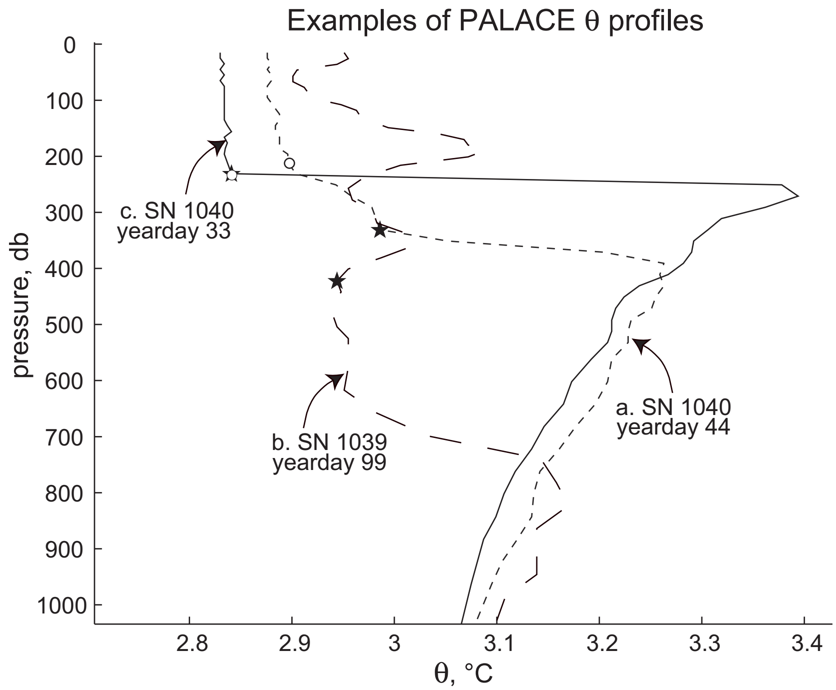

Figure 4. Three examples of PALACE potential temperature profiles. Stars mark objectively selected mixed layer bases; circles mark the manually confirmed and adjusted values. Profile a, dashed, (from float 1039, yearday 99) was excluded from further analysis due to its lack of a defined mixed layer. Profile b, dotted (from float 1040, yearday 44) had a mixed layer depth value manually adjusted shallower. Profile c, solid (from float 1040, yearday 33) is most typical; no manual adjustment to the objectively selected depth was made.

DLF data required dual strategies to compute mixed layer depth. The initial and final DLF profiles were treated in the same manner as the PALACE and CTD profiles. During the Lagrangian portion of DLF missions, however, an alternate strategy had to be employed. Determination of mixed layer depth was not possible for periods when the floats were below the mixed layer because the overlaying stratification was not known. While the floats were within the convecting layer they (and the surrounding water) would be subject to a restoring force as they approached the pycnocline and not sample this region. Thus the maximum depth reached by DLFs on transits of the convective layer should be the depth of the mixed layer.

A two-step process for mixed layer depth determination was used for the Lagrangian portion of the records. The data were first classified as within or below the mixed layer based on temperature as described below. Mixed layer depths were then defined as the maximum depths reached over a running five-day temporal window for

data determined to be within the mixed layer.

Although pressure records generally made apparent whether the float was within or below the convecting layer, utilizing the sharp thermocline that marks the bottom of the mixed layer allowed a more precise determination. A mixed layer potential temperature trend was constructed utilizing shallow DLF data (<150 db, depths well within the mixed layer). Mission times at which the recorded potential temperature exceeded the DLF mixed layer temperature trend by more than 0.02°C were excluded as being outside the mixed layer. Comparison with the pressure records confirmed this as a very effective classification scheme; the DLF pre-mission autoballast and post-mission profiles were excluded.

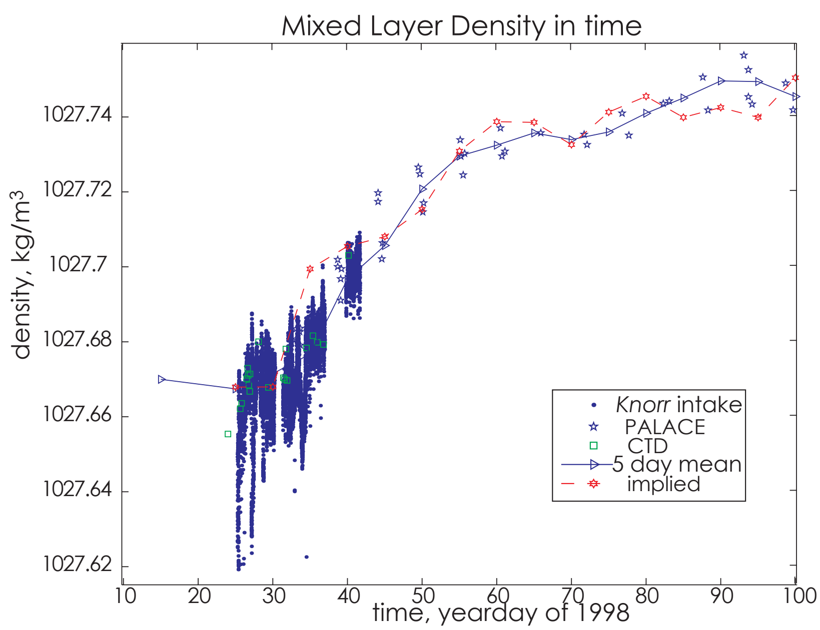

Figure 5. Mixed layer density in the central Labrador Sea during early 1998. As in Fig. 1, dots are from R/V *Knorr* intake, stars from PALACE float data, and squares from CTD data. Solid line is “background” from which departures can be calculated. Dashed line is “implied” density, i.e., potential density of CTD Station 6 at the “background” mixed layer depth.

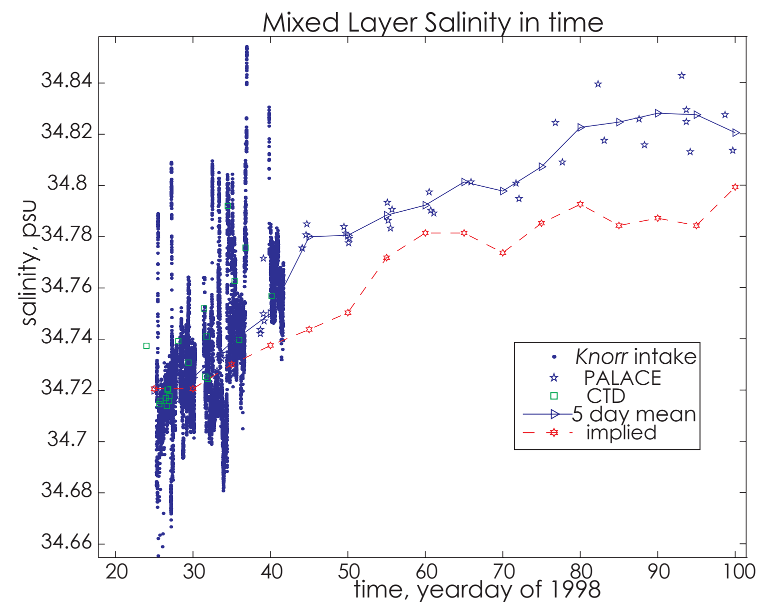

Figure 6. Mixed layer salinity as in Fig. 5. "Implied" salinity is the salinity content of CTD Station 6 mixed to the "background" mixed layer depth.

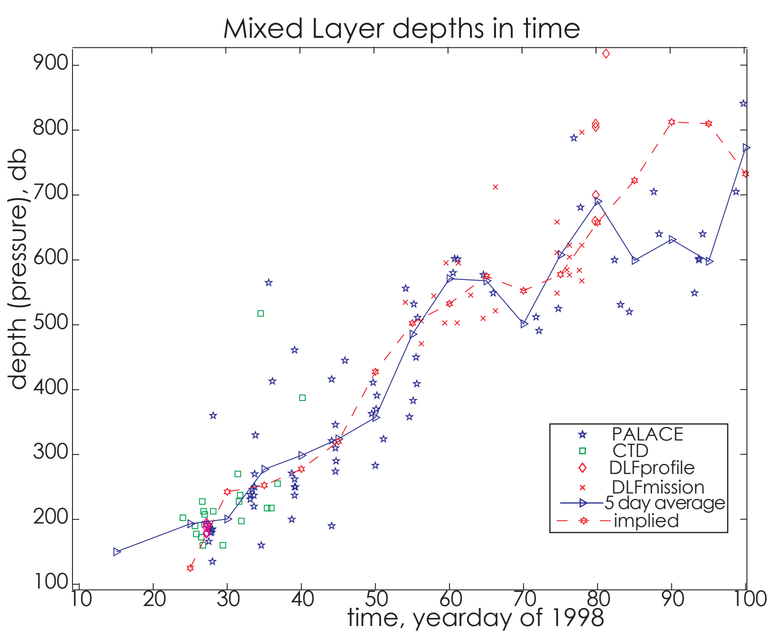

Figure 7. Mixed layer depth as in Fig. 5. "x" symbols mark data collected during the Lagrangian portion of DLF mission (within the mixed layer). Diamonds mark DLF (non-Lagrangian) profiles. Dashed line is "implied" depth, i.e., CTD Station 6 pressure at "background" potential density.

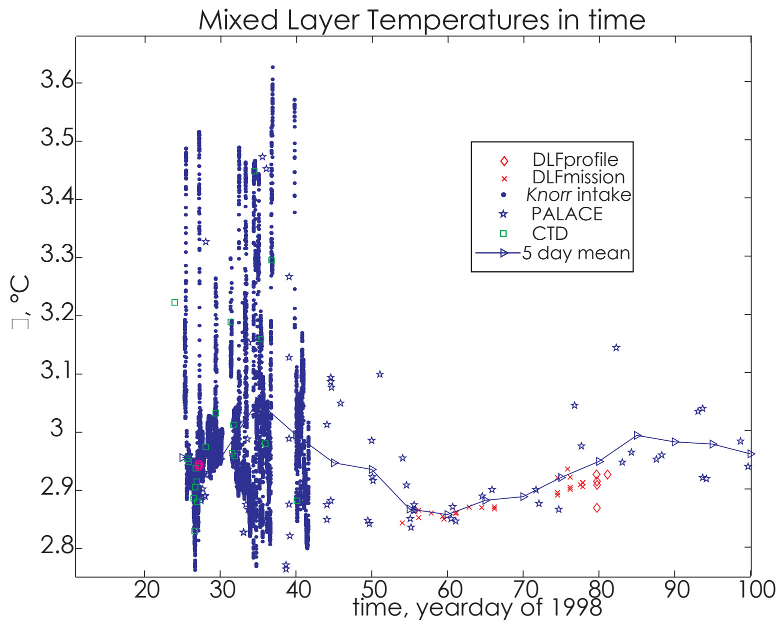

Figure 8. Mixed layer potential temperature with time as in Fig. 7

With these definitions and values the different data sets were combined to show the evolution of mixed layer depth, temperature, salinity, and density (Figs. 5–8). The mixed layer deepened from under 200 db in late January to 800 db by April (Fig. 7). Apparent in this time series is the strong variability in the region; mixed layer depth estimates often varied by 200 db at one time—a substantial variability given the relatively small area. As expected for a deepening mixed layer, the density increased through the record (Fig. 5).

To determine "background" values from the diverse data sources, a weighted, binned averaging scheme was employed. Each type of data available within a five-day bin was averaged (average CTD mixed layer depth, for example). Each of these average values was then averaged with the other data sources available within that bin. For example, for a five-day bin with four PALACE profiles, 200 intake data points, and three CTD casts, an average PALACE, intake, and CTD value was determined, then these three (equally weighted) values were averaged. In this way a representative value for each time and each variable was determined without undo emphasis on any one sensor type. (See solid lines in Figs. 5–8.) Calculating deviations from these "background" values helped account for the temporal aliasing caused by the evolution of the mixed layer in time. These data were then compared spatially in order to resolve structures in the area of study[*Steffen and D'Asaro*, 2003].

As a consistency check, "implied" mixed layer depth, density, and salinity were calculated by combining data from CTD Station 6 (collected January 27, 1998) with the observed mixed layer values at later times. The "implied" mixed layer depth was the depth at which the observed density occurred at the time of CTD Station 6. Equivalently, the density at the observed mixed layer depth at CTD Station 6 was the "implied" density. "Implied" salinity was calculated by averaging the salinity measurement of CTD Station 6 from the surface to the observed mixed layer depth. "Implied" mixed layer depth and density agreed well with observations.

4 DLF Horizontal Tracking

DLF horizontal tracking was obtained using the RAFOS receivers aboard the DLFs [*Rossby et al.*, 1986] and the four RAFOS sound sources deployed in the Labrador Sea as part of the Labrador Sea Deep Convection Experiment (see Fig. 9 for sound source locations). The RAFOS sound sources transmit a signal on a 4-hr cycle. Each source transmits its signal staggered by 0.5 hr from the others during the cycle. By calculating the delay between transmission and receipt of the signals, the float position can be triangulated. Obtaining these positions is challenged by the removal of false returns from the record, determination and correction of clock errors, and determination of the speed of sound. Two procedures for determining position are discussed here. One with a more relaxed editing scheme, non-simultaneous determination of float clock error (requiring two, rather than three, sources to be heard), and a variable speed of sound was found superior.

The receivers listen during the expected period and record the time and correlation to expected signal for the best three possible returns heard by the receiver. Every 4-hr window thus has three recorded times for each of the four sources, even if the true source signal was too weak to be detected. Therefore, the record of RAFOS returns must be carefully "cleaned" in order to remove spurious returns before position can be determined. Sound source 1, positioned behind the Eirik ridge (not evident in Fig. 9) relative to the central Labrador Sea, had consistently weak returns. Returns from this source were not used in this study.

The returns were cleaned by two methods. The first was a wholly objective routine, in which the records were edited by excluding data points for each sound source that were 4 s or more off a running five-point linear fit, then excluding those points more than 1.5 s off a new running five-point linear fit. These edited data were then

interpolated to constant 4-hr intervals. This resulted in a substantial number of windows filled by interpolated data (only 32% of windows had returns from all three sources). In order to maximize the real data employed, a second cleaning method involved a much less stringent routine with subsequent manual confirmation, which preserved 86% of the possible data.

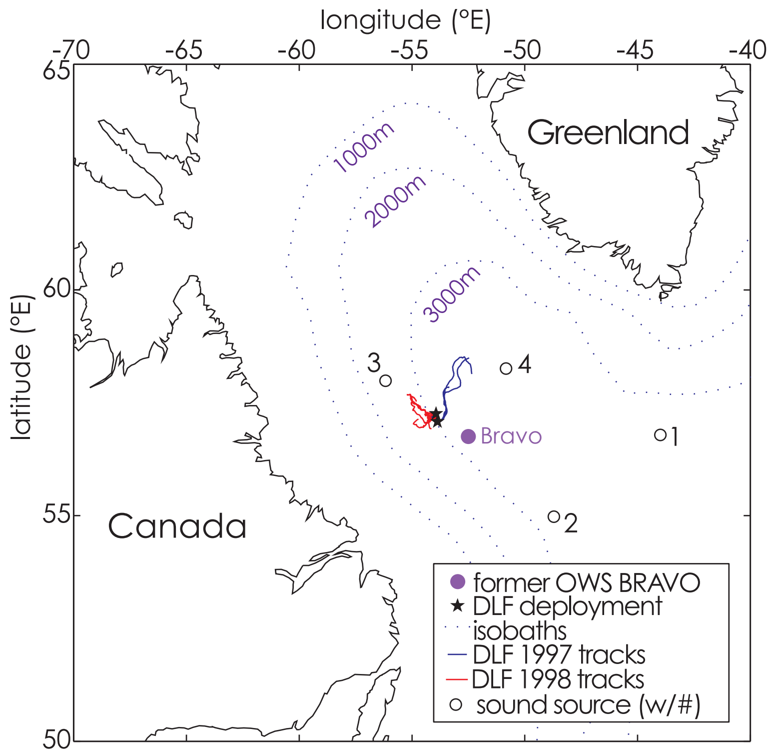

Figure 9. The Labrador Sea, with bathymetry shown dashed, the former BRAVO site indicated, the four RAFOS sound source locations shown as numbered circles, the DLF deployment locations shown as stars, and DLF tracks shown as colored lines (red for 1998 and blue for 1997)

Another challenge in determining position rests on the determination of clock errors, both the float clock and the sound source clocks. By the time of the 1998 DLF missions, the sound sources had been deployed for several years. Utilizing the first 30 returns observed by each float (at a time when the floats were near their deployment, and therefore known, position) the expected delays were compared with the observed delays for each float/source pair (Fig. 10). Intercomparisons between floats yielded source offset estimates of up to several seconds, which agreed to within the DLF digitization error (± 0.3 seconds).

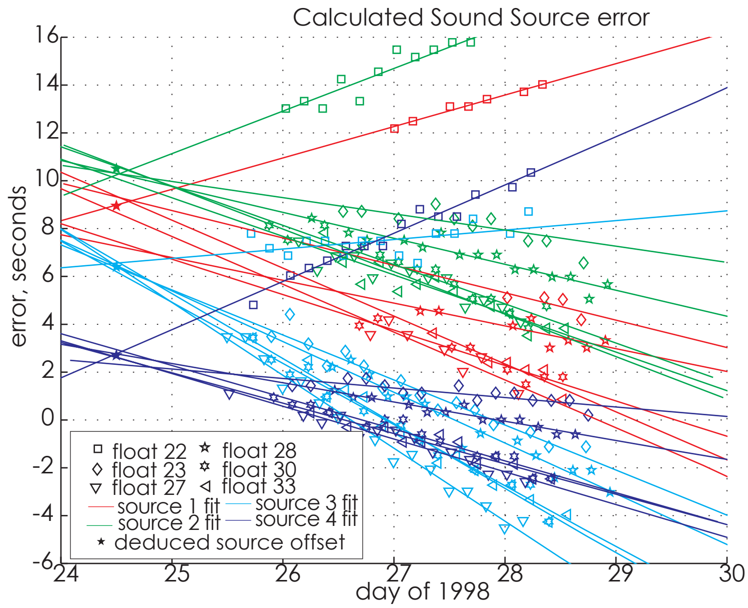

Figure 10. Returns for the first windows, coded by color for sound source and symbol for float number. Linear fits for each float/source pair are shown as colored lines. Sound source clock offset shown as solid stars.

DLF float clocks were determined to drift essentially linearly, but at a rate of up to 2 s day^{-1} [*Steffen and D'Asaro*, 2002]. To account for the float clock error, one method of position determination used the three sources to simultaneously solve the following equation for float clock offset δt and float horizontal position, x and y.

$$R_i^2 = (c(\delta t + t_i))^2 = (x - S_{xi})^2 + (y - S_{yi})^2, \tag{1}$$

where the subscript i indicates each of the three sources, R is range of the float to sound source, c the speed of sound, t the measured delay from that sound source, and S_x and S_y the sound source's position. The float clocks drifted nearly linearly in time, with a spread consistent with the digitization error, and with slopes nearly identical to those obtained from ARGOS post-mission records. Because these slopes were so well defined, a second positioning scheme was possible. Float clock error was corrected using the slopes determined from the three source method, then two sources were used to obtain a horizontal position. This second method allowed comparison of position estimates within one window derived from different pairs of sources to gain a better understanding of errors.

While three sources should imply three pairs for three positions, in this case, the geometry of source 2 and source 3 and the DLF positions made this pair unusable.

Thus the accuracy of positions were compared for the derived positions of source pairs 2 and 4, and 3 and 4. This revealed an error pattern. To test the hypothesis that this pattern was the result of variability in the speed of sound, the position equation for times when three returns were available was solved for an error in the speed of sound, c_{err}:

$$R_i^2 = ((c + c_{err})t_i)^2 = (x - S_{xi})^2 + (y - S_{yi})^2. \tag{2}$$

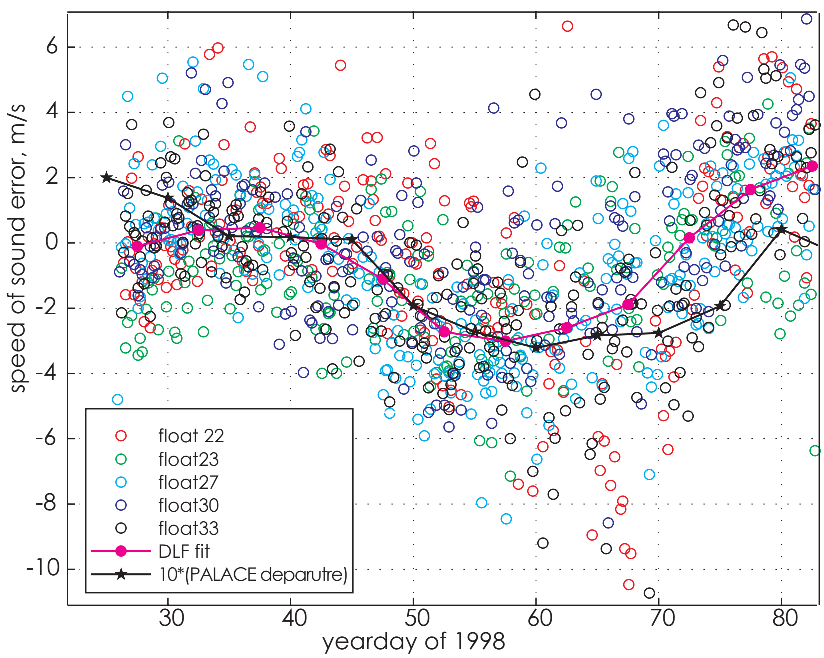

Figure 11. Calculated c_{err} for every window with signals from three RAFOS sources detected. Circles are data color-coded by float. Magenta line is fit of the DLF data with a five-day running mean. Black line is ten times the PALACE float depth-averaged c variability.

A five-day mean for the sound speed errors derived from the DLF data was used to correct the speed of sound (magenta line in Fig. 11). This small error was not revealed by comparing beginning and end positions (known from deployment and first ARGOS contact, respectively), because it is small and it is essentially 0 at mission start and mission end (the only times position is known from an alternate source). To confirm that these errors were the result of variations in sound speed, the speed of sound was calculated from PALACE data. The variation in PALACE depth-averaged sound speed was multiplied by a factor of 10 to show up on the same scale (Fig. 11). Ray paths were not calculated; the signals presumably spent a large portion of their

journeys within the variable layer. The shape of the sound speed variation derived from DLF data and the PALACE floats was remarkably similar. The variable speed of sound, represented by the magenta curve in Fig. 11, was the one used for the determination of position.

Returns from sources 3 and 4 displayed much less jitter than those from source 2. When positions determined using source 2 were inserted where source 3 was unavailable, position jumped unrealistically. Therefore, only source 3 and source 4 were used for position determination and data gaps were filled by interpolation for the tracking used by *Steffen and D'Asaro* [2003].

Choosing a two-point position determination method and reducing the selectivity of the cleaning filter tremendously reduced reliance on interpolation. With the latter method (using sources 3 and 4 and a less stringent cleaning routine), 82% of positions were determined with no interpolation filling in data gaps, and 94% of the windows contained data from one of the two sources. With the three-source method only 32% of the position windows contained data from all the sources required. With the chosen scheme, interpolation was needed to fill gaps larger than one missing window 18 times, and not needed to fill more than two adjacent windows at any point in the dataset. Additional position accuracy was also achieved by this second method because it revealed and quantified a slight variation attributable to sound speed changes over the course of the DLF missions.

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